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Radiation hydrodynamics of core-collapse supernovae: the “key” asset for a self-consistent modelling of these events

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Abstract. We have developed a specifically tailored relativistic, radiation-hydrodynamics Lagrangian code, that enables us to simulate the evolution of the main observables (light curve, evolution of photospheric velocity and temperature) in core-collapse supernova (CC-SN) events. The code features, some simulations as well as the implications of our results in connection with a possible “standardization” of the hydrogen-rich CC-SNe are briefly discussed. The possible role of this code in the development of a “CC-SNe Laboratory” for describing the evolution of a CC-SN event in a “self-consistent” way (from the main sequence up to the post-explosive phases) from a model/data comparison of light curves and spectra is also addressed.

1. Introduction

Core-collapse supernova (CC-SN) events are thought to be the final explosive evolutionary phase of stars having initial (i.e. at main sequence) mass larger than $\sim 8\text{--}10 M_{\odot}$ (e.g. Heger et al. 2003).

Despite the importance of these explosive events in astrophysics, there are still basic questions to be answered (for details see e.g. Pumo & Zampieri 2011 — PZ11 hereafter — and references therein), related to the extreme variety of CC-SNe displays and linked to the uncertainties in the modelling of stellar evolution and explosion mechanism (see e.g. Pumo et al. 2009, and references therein). In particular the exact link between the physical properties of the explosion (ejected mass, explosion energy, stellar structure and composition at the explosion) and the observational characteristics is far from being well-established, and a “self-consistent” description of CC-SN events (from the quiescent evolutionary phases up the post-explosion evolution) is still missing.

In this context, the creation of specific modelling tools that link progenitor evolution and explosion models to the main observables (i.e. light curve, evolution of photospheric velocity and temperature) of CC-SNe is of primary importance for clarifying the nature of the CC-SN events. The development of the relativistic, radiation hydrodynamics code described here represents a key step in this direction.

2. Code description and future developments

The distinctive features of the code (described in detail in Pumo, Zampieri, & Turatto 2010, and PZ11) are an accurate treatment of radiative transfer coupled to relativistic hydrodynamics, a self-consistent treatment of the evolution of the innermost ejecta taking into account the gravitational effects of the central compact remnant, and a fully implicit Lagrangian approach to the solution of the coupled non-linear finite difference system of relativistic radiation-hydro equations. With this code it is then possible to follow the fall back of material on the central remnant in a fully relativistic formalism.

Using this code, we computed a grid of 22 post-explosive models of CC-SN events. This grid enabled us to (a) study the role of the “main” parameters affecting the post-explosion evolution of the CC-SN events (namely the ejected mass, the progenitor radius, the explosion energy, and the amount of ^{56}Ni), (b) understand the physical origin of some correlations between the photometric and spectroscopic properties of hydrogen-rich CC-SNe, and (c) perform a preliminary analysis on their utilization for cosmological purposes.

All the results are fully described in PZ11. Here we recall that we are able to reproduce the main features (peak luminosity and phase at maximum) of the light curve of SN 1987A with models having initial radius $R_0 = 3 \times 10^{12}$ cm, total initial energy $E = 1$ foe, amount of ^{56}Ni $M_{\text{Ni}} = 0.07 M_\odot$, and envelope mass ranging between 16 and 18 M_\odot . The luminosity in the radioactive tail predicted by the model is lower than the observed one. This is a consequence of fallback occurring during the evolution. We found that the innermost $\sim 0.01 M_\odot$ of the envelope, containing $\sim 2.4 \times 10^{-3} M_\odot$ of ^{56}Ni , have been accreted onto the central remnant. The time evolution of the photospheric velocity and temperature of SN 1987A is also well reproduced.

We are working at present to check the validity of the results connected with the previous items (b) and (c) against a more extended grid of models that is being computed from realistic initial conditions. The aforementioned grid of models will also serve to build an extended database to be compared with observations of single SNe in order to infer their physical properties, in analogy to what already being done using models with simplified initial conditions (e.g. SN 2007od; see Inserra et al. 2011). Our medium- and long-term goal is the development of a sort of “CC-SNe Laboratory” in which our code is interfaced, in input, with other codes dealing with the calculations of the pre-SN evolution and explosive nucleosynthesis, and in output with spectral synthesis codes (for details see PZ11, and references therein). This will allow us to describe the evolution of a CC-SN event in a self-consistent way as a function of initial mass, metallicity, stellar rotation, and mass loss history of the CC-SN progenitor.

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